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Trends in Performance and Characteristics of Ultra-Stable Oscillators for Deep Space Radio Science Experiments

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Introduction:

Telecommunication systems of spacecraft on deep space missions also function as instruments for Radio Science experiments. Radio scientists utilize the telecommunication links between spacecraft and Earth to examine very small changes in the phase/frequency, amplitude, and/or polarization of radio signals to investigate a host of physical phenomena in the solar system. Several missions augmented the radio communication system with an ultra-stable oscillator (USO) in order to provide a highly stable reference signal for one-way downlink. This configuration is used in order to enable better investigations of the atmospheres of the planets occulting the line-of-sight to the spacecraft; one-way communication was required and the transponders' built-in auxiliary oscillators were neither sufficiently stable nor spectrally pure for the occultation experiments. Since Radio Science instrumentation is distributed between the spacecraft and the ground stations, the Deep Space Network (DSN) is also equipped to function as a world-class instrument for Radio Science research. For a detailed account of Radio Science experiments, methodology, key discoveries, and the DSN's historical contribution to the field, see Asmar and Renzetti (1993). The tools of Radio Science can be and have also been utilized in addressing several mission engineering challenges; e.g., characterization of spacecraft nutation and anomalous motion, antenna calibrations, and communications during surface landing phases.

Since the first quartz USO was flown on Voyager, the technology has advanced significantly, affording future missions higher sensitivity in reconstructing the temperature-pressure profiles of the atmospheres under study as well as other physical phenomena of interest to Radio Science. This paper surveys the trends in stability and spectral purity performance, design characteristics including size and mass, as well as cost and history of these clocks in space.

Science Overview:

Almost every deep space mission conducted successful Radio Science experiments, which are typically divided in two classes: propagation and celestial mechanics & gravitation, resulting in hundreds of journal publications. Examples of these experiments include: planetary atmospheric temperature-pressure profiles and ionospheric composition, structure of planetary rings, planetary gravitational fields, shapes, and masses, planetary surface characteristics, wind profiles, magnetic fields, electron content and scintillation in solar corona and solar wind, mass flux and particle distribution of comets, search for gravitational radiation, gravitational redshift, and relativistic time-delay experiments. Stable one-way downlink is essential to propagation experiments, although several aspects can be accomplished via two-way coherent links, as well as to redshift and wind profile experiments. In addition to the completed experiments to date (e.g., Mariner(s), Pioneer(s), Voyager(s), Galileo, Ulysses, Magellan, etc.), there are important planned experiments on upcoming missions (e.g., Cassini-Huygens mission to Saturn and Titan), and possible future experiments with missions in the planning stages (e.g., Pluto Express, Rosetta, Discovery missions, etc.). For a list, see Asmar and Herrera (1995).

Instrumentation:

The elements of the instrumentation required for engineering implementation on-board a spacecraft with Radio Science experiments as part of the mission objectives vary in complexity depending on the sophistication of the experiments. They include transponders (which are available on every deep space mission although some missions have considered transceivers), an attitude control system that provides for a "quiet" spacecraft, an Ultra-Stable Oscillator, translators that are needed for coherent transmission of signals not used by the primary transponder (e.g., Ka-band for the Cassini mission), and uplink signal processing equipment for proposed uplink radio occultation experiments.

With this instrumentation, the fundamental limits on sensitivity of the end-to-end system are the frequency stability, amplitude stability, signal to noise ratio, accuracy in reconstructing navigation trajectories, and media propagation effects. The frequency stability of the one-way link is typically limited by the performance of the USO.

Ultra Stable Oscillators:

The "ultra-stable" class of oscillators have been flown on Voyager I and II, Galileo orbiter, Galileo Probe, Mars Observer, and Mars Global Surveyor. These have been quartz crystal resonators. The Cassini spacecraft will carry another quartz USO and two Rubidium USOs for the Huygens Probe in support of the Doppler Wind Experiment. There are plans to fly USOs on several other future missions.

Needed to eliminate the time needed by the transponder to lock-up on the uplink during an occultation egress as well as the media effect on the uplink, USOs become the heart of the Radio Science instrumentation on-board the spacecraft. Quartz crystal resonators, relatively small in mass, volume, and power, have been easier to "space-qualify" that atomic clocks. The latter are also being considered for space flight.

The USO technology can be divided in these design classes:

1. Voyager Class: includes Voyager I and II and Galileo orbiter
2. Mars Class: Includes Mars Observer, Mars Global Surveyor, and Cassini
3. Pluto Class
4. Huygens Class
5. Galileo Probe Class

In the first class, five identical units were procured at the same time, two flew on the Voyagers, one on Galileo, and two were spares. In the second class, a flight unit and a spare were procured, one flew on Mars Observer and the re-furbished spare flew on Mars Global Surveyor. A flight unit and a spare of a similar design was later procured for the Cassini mission. In the third class, a new "tactical BVA" design is proposed for flight on the Pluto Express mission; it shows significant reduction in mass and size without compromising the performance demonstrated by the Mars class.

The Huygens Rubidium USOs were chosen over quartz due to the need for a very short warm-up time and less stringent long-term stability. The Galileo Probe USOs had similar requirements but chosen to be quartz oscillators; insufficient documentation is available on them. In the case of both probes (Huygens and Galileo Probe), one USO was on the probe as part of its transmitter chain (e.g., the Huygens TUSO) and second identical unit was on the orbiter (Cassini and Galileo) as part of the receiving chain of the orbiter signal (e.g., Huygens RUSO).

The attached tabular summary of the Ultra Stable Oscillator technology lists seven oscillators and several key parameters characterizing them, such as mass, size, power, performance measured by Allan deviation, phase noise, drift rates, environmental performance, etc. The cost estimates are, in some cases, orders in magnitude and are meant to illustrate the relative costs only (in those year dollars). Additional cost information can be obtained from possible providers.

In addition to serving as a historical summary for interested managers, scientists, and engineers, the table has two key areas to note. The first is the major improvement in the stability between the Voyager and Mars class oscillators - an order of magnitude in Allan deviation. The second area is the significant miniaturization proposed for the Pluto class oscillator.

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Ultra Stable Oscillator Technology Information Summary

Sami Asmar, JPL, 8 November 1996

Deep Space Mission	*Voyager*	*Galileo*	*Mars Observer*	*Cassini*	*Pluto*	*Huygens*	*Galileo Probe*
Maker	Freq.Elect. Inc	Freq.Elect. Inc	APL	APL	APL	DASA, Germany	(Hughes contract)
Year	1975	1975	1987	1993	1994	1993	~ 1975
Cost/Unit ($K for that year)	55	55	250	300	-	500	-
Type of Quartz Crystal Cut	AT	AT	SC	SC	SC	Rubidium	SC
Number of Ovens	2	2	1	1	1	2	2
Mass (kg)	1.1	1.1	1.3	2	0.32	2.1	?
Steady-Stat Power Consum.(W)	2.2	2.2	2.2	2.8	0.8	10.4	~ 1
Dimensions (cm LxWxH or DxL)	10.2x19.5	10.2x19.5	10.2x10.2x16.8	10.2x12.8x19.4	5.3x6.9x9.7	17x14.9x11.8	4.6x14
Resonator Frequency (MHz)	6.38	6.38	4.79	4.79	~10	6835	4.6
Nominal Output Freq. (MHz)	19.137	19.125	19.144	114.917	38.262	10.00	23.117
Assigned Deep Space Channel	18	14	20	23	16	23	n/a
USO-refer. Downlink Bands	S, X	S, X	X	S, X, Ka	X, (Ka)	S	1.387 GHz
Drift Rate (Hz/sec)	- 1.3 e -7	- 1.5 e -7	2.3 e -6	not avail	not avail	2 e -7	2 e -7
Aging/24 Hr	5 e -11	5 e -11	2 e -11	7 e -11	2 e -11	2 e -9	?
Long Term Aging /5 yrs	2 e -7	2 e -7	1 e -7	1 e -6	not avail	4 e -6	?
Temperature (/deg C)	5 e -12	5 e -12	3 e -12	2 e -12	1 e -12	4 e -12	3 e -12
Radiation (/rad)	2 e -12	2 e -12	1 e -10	1 e -10	1 e -10	2 e -14	2 e -13
Magnetic Suspt. (/Gauss)	5 e -12	5 e -12	8 e -13	5 e -13	2 e -12	5 e -11	4 e -12
Static Acceleration (/g)	1 e -9	1 e -9	3 e -9	1 e -9	1.5 e -9	1 e -11	1 e -9
Harmonic Spur (dBc)	-40	-40	-60	-60	-50	-60	?
Phase Noise 1 Hz (dBc)	-100	-100	-110	-85	(-112)	-80	?
Phase Noise 10 Hz	-108	-108	-125	-110	(-117)	-90	?
Phase Noise 100 Hz	-118	-118	-131	-120	(-127)	-110	?
Phase Noise 1 kHz	-138	-138	-131	-125	(-132)	-120	?
Allan Dev. 0.1 sec	(2 e -11)	(2 e -11)	2 e -12	1 e -12	1 e -12	6 e -11	?
Allan Dev. 1 sec	3 e -11	3 e -11	3 e -13	2 e -13	3 e -13	1 e -11	5 e -12
Allan Dev. 10 sec	4 e -12	4 e -12	1 e -13	1 e -13	1 e -13	5 e -12	?
Allan Dev. 100 sec	1 e -12	1 e -12	1 e -13	1 e -13	1 e -13	1 e -12	?
Allan Dev. 1000 sec	1 e -12	7 e -13	2 e -13	1 e -13	2 e -13	1 e -12	(1e-10/30 min)
Source of Allan Dev. Values	in-flight tests	in-flight tests	in-flight tests	contract specs	proposal	contract specs	(probe document)
Notes:	VGR 1& 2 identical	differ from GLL prob	MGS USO identical	RFS & RFIS	Tactical BVA	2 e -10/ 15 min	rad hard/shield